

11-24-00

A

Please type a plus sign (+) inside this box → ☒

PTO/SB/05 (4/98)
Approved for use through 09/30/2000. OMB 0651-0032
Patent and Trademark Office: U.S. DEPARTMENT OF COMMERCE

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

UTILITY PATENT APPLICATION TRANSMITTAL

(Only for new nonprovisional applications under 37 C.F.R. § 1.53(b))

Attorney Docket No. IB-1576 - C.I.P.

First Inventor or Application Identifier A., Paul Alivisatos

Title A-Process for Making Surfactant Capped, etc.

Express Mail Label No. EL699112854US

APPLICATION ELEMENTS

See MPEP chapter 600 concerning utility patent application contents.

ADDRESS TO:

Assistant Commissioner for Patents
Box Patent Application
Washington, DC 20231

1. ☒ Fee Transmittal Form (e.g., PTO/SB/17)
(Submit an original and a duplicate for fee processing)2. ☒ Specification [Total Pages 28]
(preferred arrangement set forth below)

- Descriptive title of the Invention
- Cross References to Related Applications
- Statement Regarding Fed sponsored R & D
- Reference to Microfiche Appendix
- Background of the Invention
- Brief Summary of the Invention
- Brief Description of the Drawings (if filed)
- Detailed Description
- Claim(s)
- Abstract of the Disclosure

3. ☒ Drawing(s) (35 U.S.C. 113) [Total Sheets 9]

4. Oath or Declaration [Total Pages 37]

- a. ☐ Newly executed (original or copy)
- b. ☐ Copy from a prior application (37 C.F.R. § 1.63(d))
(for continuation/divisional with Box 16 completed)
- i. ☐ DELETION OF INVENTOR(S)
Signed statement attached deleting
inventor(s) named in the prior application,
see 37 C.F.R. §§ 1.63(d)(2) and 1.33(b).

* NOTE FOR ITEMS 1 & 13 IN ORDER TO BE ENTITLED TO PAY SMALL ENTITY
FEES, A SMALL ENTITY STATEMENT IS REQUIRED (37 C.F.R. § 1.27), EXCEPT
IF ONE FILED IN A PRIOR APPLICATION IS RELIED UPON (37 C.F.R. § 1.28).

5. ☐ Microfiche Computer Program (Appendix)6. Nucleotide and/or Amino Acid Sequence Submission
(if applicable, all necessary)

- a. ☐ Computer Readable Copy
- b. ☐ Paper Copy (identical to computer copy)
- c. ☐ Statement verifying identity of above copies

ACCOMPANYING APPLICATION PARTS

- 7. ☐ Assignment Papers (cover sheet & document(s))
- 8. ☐ 37 C.F.R. § 3.73(b) Statement ☒ Power of Attorney
(when there is an assignee)
- 9. ☐ English Translation Document (if applicable)
- 10. ☐ Information Disclosure Statement (IDS)/PTO-1449 ☐ Copies of IDS Citations
- 11. ☐ Preliminary Amendment
- 12. ☒ Return Receipt Postcard (MPEP 503)
(Should be specifically itemized)
- 13. ☒ * Small Entity Statement(s) ☐ Statement filed in prior application
(PTO/SB/09-12) Status still proper and desired
- 14. ☐ Certified Copy of Priority Document(s)
(if foreign priority is claimed)
- 15. ☐ Other: _____

16. If a CONTINUING APPLICATION, check appropriate box, and supply the requisite information below and in a preliminary amendment:

☐ Continuation ☐ Divisional ☒ Continuation-in-part (CIP)

of prior application No. _____/_____

Prior application information: Examiner _____

Group / Art Unit: _____

For CONTINUATION or DIVISIONAL APPS only: The entire disclosure of the prior application, from which an oath or declaration is supplied under Box 4b, is considered a part of the disclosure of the accompanying continuation or divisional application and is hereby incorporated by reference. The incorporation can only be relied upon when a portion has been inadvertently omitted from the submitted application parts.

17. CORRESPONDENCE ADDRESS

☐ Customer Number or Bar Code Labelor ☐ Correspondence address below

(Insert Customer No. or Attach bar code label here)

| | | | | | |
|---------|--|-----------|--------------|----------|-------|
| Name | Paul R. Martin | | | | |
| Address | Lawrence Berkeley National Laboratory, 1 Cyclotron Road M/S 90-1121 | | | | |
| City | Berkeley | State | CA | Zip Code | 94720 |
| Country | Alameda | Telephone | 510-486-6503 | Fax | |

| | | | |
|-------------------|-----------------------|-----------------------------------|------------|
| Name (Print/Type) | Paul R. Martin | Registration No. (Attorney/Agent) | 24,593 |
| Signature | <i>Paul R. Martin</i> | Date | 11-21-2000 |

Burden Hour Statement: This form is estimated to take 0.2 hours to complete. Time will vary depending upon the needs of the individual case. Any comments on the amount of time you are required to complete this form should be sent to the Chief Information Officer, Patent and Trademark Office, Washington, DC 20231. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Assistant Commissioner for Patents, Box Patent Application, Washington, DC 20231.

JC867 U.S. PTO

11/22/00

09721126

11/22/00
JC867 U.S. PTO
09721126

FEE TRANSMITTAL

for FY 2000

Patent fees are subject to annual revision.
Small Entity payments must be supported by a small entity statement,
otherwise large entity fees must be paid. See Forms PTO/SB/09-12.
See 37 C.F.R. §§ 1.27 and 1.28.

TOTAL AMOUNT OF PAYMENT (\$) 423

Complete if Known

| | |
|----------------------|--------------------|
| Application Number | Unassigned |
| Filing Date | |
| First Named Inventor | A. Paul Alivisatos |
| Examiner Name | Unassigned |
| Group / Art Unit | |
| Attorney Docket No. | IB-1576 C.I.P. |

METHOD OF PAYMENT (check one)

1. ☒ The Commissioner is hereby authorized to charge indicated fees and credit any overpayments to:

Deposit Account Number 120690

Deposit Account Name Lawrence Berkeley National Lab

☒ Charge Any Additional Fee Required Under 37 CFR §§ 1.16 and 1.17

2. ☐ Payment Enclosed:
☐ Check ☐ Money Order ☐ Other

FEE CALCULATION

1. BASIC FILING FEE

| Large Entity Fee Code (\$) | Small Entity Fee Code (\$) | Fee Description | Fee Paid |
|----------------------------|----------------------------|------------------------|----------|
| 101 690 | 201 345 | Utility filing fee | 345 |
| 106 310 | 206 155 | Design filing fee | |
| 107 480 | 207 240 | Plant filing fee | |
| 108 690 | 208 345 | Reissue filing fee | |
| 114 150 | 214 75 | Provisional filing fee | |

SUBTOTAL (1) (\$) 345

2. EXTRA CLAIM FEES

| Total Claims | Extra Claims | Fee from below | Fee Paid |
|--------------------------------|--------------|----------------|----------|
| 16 - 20** = 0 | 0 | 0 | 0 |
| Independent Claims 5 - 3** = 2 | 2 | 39 | 78 |
| Multiple Dependent | | | |

**or number previously paid, if greater; For Reissues, see below

| Large Entity Fee Code (\$) | Small Entity Fee Code (\$) | Fee Description |
|----------------------------|----------------------------|--|
| 103 18 | 203 9 | Claims in excess of 20 |
| 102 78 | 202 39 | Independent claims in excess of 3 |
| 104 260 | 204 130 | Multiple dependent claim, if not paid |
| 109 78 | 209 39 | ** Reissue independent claims over original patent |
| 110 18 | 210 9 | ** Reissue claims in excess of 20 and over original patent |

SUBTOTAL (2) (\$) 78

FEE CALCULATION (continued)

3. ADDITIONAL FEES

| Large Entity Fee Code (\$) | Small Entity Fee Code (\$) | Fee Description | Fee Paid |
|----------------------------|----------------------------|--|----------|
| 105 130 | 205 65 | Surcharge - late filing fee or oath | |
| 127 50 | 227 25 | Surcharge - late provisional filing fee or cover sheet. | |
| 139 130 | 139 130 | Non-English specification | |
| 147 2,520 | 147 2,520 | For filing a request for reexamination | |
| 112 920* | 112 920* | Requesting publication of SIR prior to Examiner action | |
| 113 1,840* | 113 1,840* | Requesting publication of SIR after Examiner action | |
| 115 110 | 215 55 | Extension for reply within first month | |
| 116 380 | 216 190 | Extension for reply within second month | |
| 117 870 | 217 435 | Extension for reply within third month | |
| 118 1,360 | 218 680 | Extension for reply within fourth month | |
| 128 1,850 | 228 925 | Extension for reply within fifth month | |
| 119 300 | 219 150 | Notice of Appeal | |
| 120 300 | 220 150 | Filing a brief in support of an appeal | |
| 121 260 | 221 130 | Request for oral hearing | |
| 138 1,510 | 138 1,510 | Petition to institute a public use proceeding | |
| 140 110 | 240 55 | Petition to revive - unavoidable | |
| 141 1,210 | 241 605 | Petition to revive - unintentional | |
| 142 1,210 | 242 605 | Utility issue fee (or reissue) | |
| 143 430 | 243 215 | Design issue fee | |
| 144 580 | 244 290 | Plant issue fee | |
| 122 130 | 122 130 | Petitions to the Commissioner | |
| 123 50 | 123 50 | Petitions related to provisional applications | |
| 126 240 | 126 240 | Submission of Information Disclosure Stmt | |
| 581 40 | 581 40 | Recording each patent assignment per property (times number of properties) | |
| 146 690 | 246 345 | Filing a submission after final rejection (37 CFR § 1.129(a)) | |
| 149 690 | 249 345 | For each additional invention to be examined (37 CFR § 1.129(b)) | |

Other fee (specify) _____

Other fee (specify) _____

* Reduced by Basic Filing Fee Paid

SUBTOTAL (3) (\$) _____

SUBMITTED BY

Name (Print/Type) Paul R. Martin
Signature Paul R. Martin

Registration No. (Attorney/Agent) 24,593

Complete (if applicable)

Telephone (510) 486-6503

Date 11-21-99

WARNING:

Information on this form may become public. Credit card information should not be included on this form. Provide credit card information and authorization on PTO-2038.

Burden Hour Statement: This form is estimated to take 0.2 hours to complete. Time will vary depending upon the needs of the individual case. Any comments on the amount of time you are required to complete this form should be sent to the Chief Information Officer, Patent and Trademark Office, Washington, DC 20231. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Assistant Commissioner for Patents, Washington, DC 20231.

Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number

| | |
|---|--|
| STATEMENT CLAIMING SMALL ENTITY STATUS (37 CFR 1.9(f) & 1.27(d))—NONPROFIT ORGANIZATION | Docket Number (Optional) IB-1576 CIP |
| Applicant, Patent Trademark Design : <u>A. Paul Alivisatos, et al.</u> | |
| Application Patent Trademark Design No.: <u>Not Yet Assigned</u> | |
| Filed Patent Trademark Design : _____ | |
| Title: <u>A PROCESS FOR MAKING SURFACTANT CAPPED METAL OXIDE</u> <u>NANOCRYSTALS, ETC.</u> | |
| I hereby state that I am an official empowered to act on behalf of the nonprofit organization identified below: | |
| NAME OF NONPROFIT ORGANIZATION <u>The Regents, Univ. of Calif.</u> | |
| ADDRESS OF NONPROFIT ORGANIZATION <u>1111 Franklin Street, 12th Floor, Oakland, CA</u> <u>94607-5200</u> | |
| TYPE OF NONPROFIT ORGANIZATION: | |
| <input checked="" type="checkbox"/> UNIVERSITY OR OTHER INSTITUTION OF HIGHER EDUCATION | |
| <input type="checkbox"/> TAX EXEMPT UNDER INTERNAL REVENUE SERVICE CODE (26 U.S.C. 501(a) and 501(c)(3)) | |
| <input type="checkbox"/> NONPROFIT SCIENTIFIC OR EDUCATIONAL UNDER STATUTE OF STATE OF THE UNITED STATES OF AMERICA (NAME OF STATE _____) (CITATION OF STATUTE _____) | |
| <input type="checkbox"/> WOULD QUALIFY AS TAX EXEMPT UNDER INTERNAL REVENUE SERVICE CODE (26 U.S.C. 501(a) and 501(c)(3)) IF LOCATED IN THE UNITED STATES OF AMERICA | |
| <input type="checkbox"/> WOULD QUALIFY AS NONPROFIT SCIENTIFIC OR EDUCATIONAL UNDER STATUTE OF STATE OF THE UNITED STATES OF AMERICA IF LOCATED IN THE UNITED STATES OF AMERICA (NAME OF STATE _____) (CITATION OF STATUTE _____) | |
| I hereby state that the nonprofit organization identified above qualifies as a nonprofit organization as defined in 37 CFR 1.9(e) for purposes of paying reduced fees to the United States Patent and Trademark Office regarding the invention described in: | |
| <input checked="" type="checkbox"/> the specification filed herewith with title as listed above. <input type="checkbox"/> the application identified above. <input type="checkbox"/> the patent identified above. | |
| I hereby state that rights under contract or law have been conveyed to and remain with the nonprofit organization regarding the above identified invention. If the rights held by the nonprofit organization are not exclusive, each individual, concern, or organization having rights in the invention must file separate statements as to their status as small entities and that no rights to the invention are held by any person, other than the inventor, who would not qualify as an independent inventor under 37 CFR 1.9(c) if that person made the invention, or by any concern which would not qualify as a small business concern under 37 CFR 1.9(d) or a nonprofit organization under 37 CFR 1.9(e). | |
| Each person, concern, or organization having any rights in the invention is listed below: | |
| <input type="checkbox"/> no such person, concern, or organization exists. <input checked="" type="checkbox"/> each such person, concern, or organization is listed below. | |
| I acknowledge the duty to file, in this application or patent, notification of any change in status resulting in loss of entitlement to small entity status prior to paying, or at the time of paying, the earliest of the issue fee or any maintenance fee due after the date on which status as a small entity is no longer appropriate. (37 CFR 1.28(b)) | |
| NAME OF PERSON SIGNING <u>Paul R. Martin</u> | |
| TITLE IN ORGANIZATION OF PERSON SIGNING <u>Attorney, Patent Department</u> | |
| ADDRESS OF PERSON SIGNING <u>1 Cyclotron Road - MS 90-1121 Berkeley, CA 94720 Alameda</u> | |
| SIGNATURE | <u><i>Paul R. Martin</i></u> |
| DATE | <u>11-21-2000</u> |

Burden Hour Statement: This form is estimated to take 0.2 hours to complete. Time will vary depending upon the needs of the individual case. Any comments on the amount of time you are required to complete this form should be sent to the Chief Information Officer, Patent and Trademark Office, Washington DC 20231. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Assistant Commissioner for Patents, Washington DC 20231.

00224736 260

**A PROCESS FOR MAKING SURFACTANT
CAPPED NANOCRYSTALS**

A. Paul Alivisatos (U.S. citizen)
5941 Estates Dr.
Oakland, CA 94611

and

Jorg Rockenberger (citizen of Germany)
2323 Hearst Ave.
Berkeley, CA 94709

ATTORNEY DOCKET NO. IB-1576 C.I.P.

CERTIFICATION UNDER 37 C.F.R. 1.10*

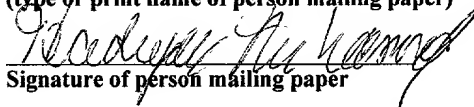
*(Express Mail label number is **mandatory**.)*

(Express Mail certification is optional.)

I hereby certify that this correspondence is being deposited with the United States Postal Service on this date 11/21/00
Hadiyah Muhammad, in an envelope as "Express Mail Post Office to Addressee," mailing Label Number
EL699112854US, addressed to the: Assistant Commissioner for Patents, Washington, D.C. 20231.

Hadiyah Muhammad

(type or print name of person mailing paper)


Signature of person mailing paper

**A PROCESS FOR MAKING SURFACTANT CAPPED METAL OXIDE
NANOCRYSTALS,
AND PRODUCTS PRODUCED BY THE PROCESS**

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority under 35 U.S.C. Sec. 119 (e), based on Provisional patent application Ser. No. 60/ 162,299, filed 10/28/99, and co-pending application Ser. No. _____, entitled, A Process For Making Surfactant Capped Nanocrystals, filed Oct. 30, 2000, both of which are incorporated by reference herein in their entirety.

STATEMENT REGARDING FEDERAL SPONSORSHIP

The invention described herein arose in the course of, or under, contract No. DE-AC03-SF00098 between the United States Department of Energy and the Regents, University of California for the operation of the Ernest Orlando Lawrence Berkeley National Laboratory.

BACKGROUND OF THE INVENTION

This invention relates to a process for making dispersable surfactant capped nanocrystals. More particularly, it relates to a process for making dispersable surfactant capped nanocrystals of metal oxides with non-hydroxylated particle surfaces using a non-hydrolytic single precursor approach, and to the nanocrystals made thereby. Still more particularly, it relates to a process for making dispersable surfactant capped nanocrystals of transition metal oxides.

The advent of new methods to prepare semiconductor and metal nanocrystals, specifically the injection of molecular precursors into hot organic surfactants, has yielded markedly improved samples with good size control, narrow size distributions, and good crystallinity of individual and dispersable nanocrystals (see references 1-3). It is of considerable interest to apply these methods to the synthesis of metal oxide nanocrystals, particularly transition metal oxide nanoparticles, which typically are prepared by methods involving water as solvent or reactant (4-9). Using nonhydrolytic preparations of metal oxide nanocrystals at high temperature in organic surfactants in the absence of air or water, one observes markedly different properties with respect to defect structure and surface composition. So far as applicants are aware, there has been only one example of the solution-based nonhydrolytic synthesis of individual TiO_2 nanocrystals (10). Metal oxide nanocrystals with nonhydroxylated surfaces are believed to have significant advantages for applications in catalysis, ceramics, energy storage, magnetic data storage, sensors, ferrofluids, etc.

The following references contain useful background information pertaining to this invention, and are incorporated by reference herein in their entirety.

1. Murray, C. B.; Norris, D. J.; Bawendi, M. G. J. Am. Chem. Soc. 1993, 115, 8706-8715.
2. Peng, X.; Wickham, J.; Alivisatos, A. P. J. Am. Chem. Soc. 1998, 120, 5343-5344.
3. Sun, S.; Murray, C. J. Appl. Phys. 1999, 85, 4325-4330.
4. Charles, S. W.; Popplewell, J. Ferromagnetic Materials; Northholland Publishing Co.: Amsterdam, New York, Oxford, 1982; Vol. 2.
5. Brinker, C. J.; Scherer, G. W. Sol-Gel Science; Academic Press: San Diego, 1990.

6. Ziolo, R. F.; Giannelis, E. P.; Weinstein, B. A.; O'Horo, M. P.; Ganguly, B. N.; Mehrotra, V.; Russell, M. W.; Huffman, D.R. *Science* 1992, 257, 219-223.
7. Matijevic, E. *Chem. Mater.* 1993, 5, 412.
8. Moumen, N.; Pileni, M. P. *Chem. Mater.* 1996, 8, 1128.
9. Ying, J. Y. Special Issue: Sol-Gel Derived Materials. In *Chem. Mater.* 1997, 9, 2247-2670.
10. Trentler, T. J.; Denler, T. E.; Bertone, J. F.; Agrawal, A.; Colvin, V. L. *J. Am. Chem. Soc.* 1999, 121, 1613-1614.
11. Comprehensive coordination chemistry: the synthesis, reactions, properties & applications of coordination compounds, 1st ed.; Pergamon Press: Oxford, England, 1987; Vol. 2, Chapter 15.9.2.
12. Helm, D. v. d.; Merritt, L. L.; Degeilh, R.; MacGillavry, C. H. *Acta Crystallogr.* 1965, 18, 355-362.
13. Elerman, Y.; Atakol, O.; Svoboda, I.; Geselle, M. *Acta Crystallogr. C* 1995, 51, 1520-1522.
14. Tamaki, K.; Okabe, N. *Acta Crystallogr. C* 1996, 52, 1612-1614.
15. Kellner, R.; Prokopowski, P. *Anal. Chim. Acta* 1976, 86, 175-184.
16. Nolze, G.; Kraus, W. *Powder Diffr.* 1998, 13, 256-259.
17. Shmakov, A. N.; Kryukova, G. N.; Tsybulya, S. V.; Chuvilin, A. L.; Solovyeva, L. P. *J. Appl. Crystallogr.* 1995, 28, 141.
18. Jarosch, D. *Mineral. Petrol.* 1987, 37, 15-23.
19. Neuburger, M. C. *Z. Phys.* 1930, 67, 845-850.
20. Cullity, B. D. *Elements of X-ray Diffraction*, 2nd ed.; Addison-Wesley: Reading, MA, 1978.
21. Bentzon, M. D.; Wonterghem, J. v.; Morup, S.; Tholen, A.; Koch, C. J. W. *Philos. Mag. B* 1989, 60, 169-178.
22. Murray, C. B.; Kagan, C. R.; Bawendi, M. G. *Science* 1995, 270, 1335-1338.
23. Chemseddine, A.; Weller, H. *Ber. Bunsen-Ges. Phys. Chem.* 1993, 97, 636-637.

24. Fleet, M. E. Acta Crystallogr. B 1981, 37, 917-920.
25. Cornell, R. M.; Schwertmann, U. The Iron Oxides-Structure, Properties, Reactions, Occurrence and Uses, 1st ed.; VCH Verlagsgesellschaft: Weinheim, Germany, 1996.
26. *Reagent Chemicals: American Chemical Society Specifications*; 8th ed.; American Chemical Society: Washington, DC, 1993.

SUMMARY OF THE INVENTION

It is an object of this invention to provide a non-hydrolytic process for the preparation of metal oxide nanocrystals.

It is a further object of this invention to provide a non-hydrolytic process for the preparation of transition metal oxide nanocrystals having non-hydroxylated surfactant capped surfaces.

It is a further object of this invention to provide surfactant capped metal oxide nanocrystals with non-hydroxylated surfaces which are dispersable in organic solvents, and a process of preparing them.

It is a still further object of this invention to provide new and novel metal oxide nanocrystals.

These, and other objects are achieved by (a) mixing a solution of a metal cupferron precursor complex of the formula $M^X\text{Cup}_X$, wherein M^X is a metal ion in the oxidation state X selected from the group consisting of elements in Group 2, Group 3 – 12 of the 4th period, Group 3 – 6 of the 5th and 6th period, Group 10 – 12 of the 5th period, Group 12 of the 6th period, and Group 13th to 15th, and the Lanthanide and Actinide series of the periodic table, and Cup is a N-substituted N-Nitroso hydroxylamine, with a coordinating surfactant, and (b) heating the mixture at a temperature and for a sufficient period of

time to cause thermal decomposition of the $M^X\text{Cup}_X$ precursor and formation of the desired nanocrystals.

As used herein, the term “coordinating surfactant” means an organic molecule consisting of a polar headgroup and an apolar group providing stabilization against coagulation and precipitation of particles by binding to particle surfaces through the polar headgroup and allowing dispersion of particles in aliphatic, aromatic and halogenated hydrocarbons.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows the result of the thermal analysis of iron, manganese and copper cupferronate in a TGA/DTA apparatus under N_2 -flow (left). To the right, the xrd patterns of the respective decomposition products are displayed.

Figure 2 and 3 present low-resolution TEM images as well as XRD patterns of $\gamma\text{-Fe}_2\text{O}_3$, Mn_3O_4 , and Cu_2O nanocrystals, respectively.

Figure 4 presents low-resolution TEM images as well as derived particle size distributions of $\gamma\text{-Fe}_2\text{O}_3$ nanocrystals prepared under varying synthesis conditions.

Figure 5 shows particle size distributions derived from low-resolution TEM imaging as a function of refluxing time after the precursor injection.

Figure 6 describes the increasing average particle size as the reaction precipitate is subsequently extracted with Toluene.

Figure 7, shows a low-resolution TEM image of a monolayer of individual $\gamma\text{-Fe}_2\text{O}_3$ nanocrystals (10.0 ± 1.5 nm) covering an area bigger than $2 \mu\text{m}^2$. Top left: High-resolution TEM image of one of the nanocrystals in this sample. The indicated lattice

plane distances correspond to the (113) and (201) lattice planes of tetragonal $\gamma\text{-Fe}_2\text{O}_3$ with ordered superlattice of the cation vacancies. Top right: FFT of the high-resolution TEM image looking down the [51-2] zone-axis.

Figure 8 and 9 present XRD patterns as well as FT-IR spectra of the iron, manganese and copper cupferronates, respectively.

DETAILED DESCRIPTION OF THE INVENTION

We have now discovered a new nonhydrolytic single-precursor approach to the synthesis of dispersable nanocrystals of metal oxides, particularly transition metal oxides.

The process comprises: (a) mixing a solution of a metal cupferron precursor complex of the formula $\text{M}^{\text{X}}\text{Cup}_x$, wherein M^{X} is a metal ion in the oxidation state X selected from the group consisting of elements in Group 2, Group 3 – 12 of the 4th period, Group 3 – 6 of the 5th and 6th period, Group 10 – 12 of the 5th period, Group 12 of the 6th period, and Group 13th to 15th, and the Lanthanide and Actinide series of the periodic table, and Cup is a N-substituted N-Nitroso hydroxylamine, with a coordinating surfactant, and (b) heating the mixture at a temperature and for a sufficient period of time to cause thermal decomposition of the $\text{M}^{\text{X}}\text{Cup}_x$ precursor and formation of the desired nanocrystals.

While the process described below is focused primarily on the preparation of transition metal oxide nanocrystals, it is equally applicable to the formation of any metal oxide nanocrystal where the metal (M^X) is a metal ion in the oxidation state X selected from the group consisting of elements in Group 2, Group 3 – 12 of the 4th period, Group 3 – 6 of the 5th and 6th period, Group 10 – 12 of the 5th period, Group 12 of the 6th period, and Group 13th to 15th, and the Lanthanide and Actinide series of the periodic table.

The value for X will vary, depending on which metal is used in the formation of the precursor, and the oxidation state of the metal. In general, however, X will range from 1 to 4.

Metal Cupferron complexes M^XCup_X (M: metal ion; Cup: N-nitroso N - phenylhydroxylamine, $C_6H_5N(NO)O^-$), with the metal ion coordinated via the oxygen atoms of the Cup ligand in a bidentate manner, proved to be promising as molecular precursors. Metal cupferronates are used in the precipitation or extraction of metal ions from aqueous solution, and are easily prepared for many metal elements (11). In the following, we demonstrate that injecting solutions of metal Cupferron complexes in octylamine into long-chain amines at 250-300 °C yields nanocrystals of iron oxide, manganese oxide, and copper oxide. These nanocrystals range from 4 to 10 nm in diameter, are crystalline, and are dispersable in organic solvents. As Cupferron complexes are available for almost all metal elements, the use of this precursor offers an interesting general approach to metal oxide nanocrystals.

The preparation of the metal Cupferron precursor is based on the precipitation of metal ions from aqueous solution at a specific pH with Cupferron, the ammonium salt of N-nitroso N-phenylhydroxylamine (details of the synthesis and characterization of the metal cupferronates $M^x\text{Cup}_x$ (M: Fe, Cu, Mn) are provided infra). In all three cases the elemental analysis and the powder X-ray diffraction (XRD) patterns agreed well with single-crystal data (12-14). In addition, FT-IR spectroscopy excluded the presence of excess Cupferron, water, or solvent molecules, and agreed well with results given in the literature (15).

Dried powders of metal cupferronates show sharp decomposition temperatures (see fig. 1, left) of 180 °C, 230 °C, and 205 °C for FeCup_3 , MnCup_2 , and CuCup_2 , respectively, when heated in a DTA/TGA apparatus under nitrogen ($\Delta T = 10\text{ °C / min.}$, 25 °C – 500 °C). In fig. 1 right, the XRDs of the respective decomposition products reveal that they consist of $\gamma\text{-Fe}_2\text{O}_3$, MnO, and Cu. The latter is a consequence of the reduction of $\text{CuO/Cu}_2\text{O}$ by the reducing atmosphere given by the organic decomposition products of the Cupferron complex. This result proves that metal Cupferron complexes can indeed act as molecular precursors for transition metal oxides in the absence of O_2 and H_2O .

In the following, a typical synthesis yielding iron oxide nanocrystals with 6-7 nm particle diameters is described. To remove oxygen and water, 7 g of trioctylamine was heated to 100 °C for 1-1.5 h and repeatedly evacuated to 20 mTorr and purged with Ar. A solution of 0.3 M FeCup_3 in octylamine was treated the same way at 60 °C. The reaction was initiated by the rapid injection of 4 mL of FeCup_3 stock solution into the

By addition of a 3-fold volume excess of methanol, the iron oxide nanocrystals could be reprecipitated as a brown powder. Adding methanol to the supernatant of the reaction led to a brown precipitate of iron oxide nanocrystals, which could also be redispersed and reprecipitated by suitable solvents. For both fractions, dispersion and reprecipitation could be repeated several times.

9 of 37

Similar procedures were used in the synthesis of manganese oxide and copper oxide nanocrystals. In the case of manganese oxide, 4 ml of a 0.3 M solution of MnCuP_2 in octylamine were injected into 7 g trioctylamine at 360 °C and refluxed for 10 min. at 275 °C. An orange precipitate was obtained after the reaction, which changed color to brown upon dispersion in toluene. Low-resolution TEM images (see fig. 2, middle) of this dispersion indicated the presence of 12.0 ± 4.7 nm Mn_3O_4 particles.

In the case of CuCuP_2 , hexadecylamine was used as a surfactant to disperse the precipitated nanocrystalline copper oxide in organic solvents like toluene, hexane, CHCl_3 etc. In addition, the reaction had to be stopped immediately after injection since the formation of metallic Cu instead of the copper oxide is favored at high temperatures under the strongly reducing conditions of the reaction. In detail, 2 ml of a 0.3 M solution of CuCuP_2 in octylamine were injected into 5.5 g hexadecylamine at 250 °C. The reaction was stopped by removing the heat as soon as the temperature reached again 230 °C. The average particle size as determined from low-resolution TEM imaging is 6.9 ± 2.5 nm (see fig. 2, right).

Powder XRD reveals the nanocrystalline nature of the described samples (Figure 3). The diffraction patterns were fitted with the program PowderCell (16) using structure data for $\gamma\text{-Fe}_2\text{O}_3$, Mn_3O_4 , and Cu_2O as models (17-19). Using the Debye-Scherrer equation (20), a crystallite size was determined for every reflection, and all were averaged to give the mean values reported in Figure 3. These averaged crystallite sizes are in good agreement with mean diameters determined from low-resolution TEM imaging (compare with results in fig. 2).

Particles with average sizes down to 4 nm were synthesized by lowering the injection temperature and/or lowering the injected precursor concentration. For instance, injecting the FeCu_3 precursor solution at 250 °C and refluxing at 200 °C for 30 min, instead of 300 °C and 225 °C as in the sample of Figure 2 (see also fig. 4, left), yields $\gamma\text{-Fe}_2\text{O}_3$ nanocrystals 5.2 ± 1.5 nm in size (see fig. 4 middle). However, the injection of an additional 2 mL of precursor solution after 5 min of refluxing at 200 °C results in particles with diameters of 6.1 ± 1.8 nm (see fig. 4 right).

The influence of the reflux time is shown in fig. 5 for an injection of 4 ml 0.3 M $\text{FeCu}_3/\text{Octylamine}$ solution into 7 g trioctylamine at 250 °C and subsequent refluxing at 200 °C. Apparently, the particle growth is essentially finished after 10 min. and only a small increase in the width of the size distribution is observed with longer refluxing time. This behavior is similar to the growth kinetics of semiconductor nanocrystals.⁽²⁾ However, further studies are necessary to achieve a similar understanding of the growth kinetics of oxide nanocrystals.

In all cases it was observed that subsequent extractions of the reaction precipitate with small amounts of toluene yielded fractions containing continuously bigger particles. In the case of the preparation with an additional secondary injection, each subsequent extraction of the reaction precipitate resulted in approximately a 1 nm increase in the average particle diameter (see fig. 6). Consequently, the fifth fraction contained $\gamma\text{-Fe}_2\text{O}_3$ nanocrystals which were 10.0 ± 1.5 nm in diameter. A low-resolution TEM image of this fraction is shown in Figure 7. Apparently, the slow evaporation of a dispersion of nanocrystals in toluene on a TEM grid leads to the formation of an extended monolayer of particles. The covered area is larger than $2 \mu\text{m}^2$ and extends beyond the part shown in

Figure 2. Each particle is separated from neighboring particles by its shell of surfactant. Currently, the relatively broad size distribution of 15% prevents the formation of ordered superlattices as observed with other systems (3,21,22) However, we believe that by using size-selective precipitation (23), in addition to size-selective extraction during the isolation process, we will be able to achieve size distributions with less than 10% standard deviation.

The crystallinity of these particles is revealed by high-resolution TEM imaging as shown in Figure 7 (top left). The observed lattice plane distances of 4.77 Å and 4.11 Å, as well as the angle of about 50° between the crossed fringes, indicate the presence of tetragonal $\gamma\text{-Fe}_2\text{O}_3$ with an ordered superlattice of cation vacancies (17). The corresponding lattice planes are (113) and (201), respectively, and the FFT (top right) of the high-resolution image indicates that the particle was imaged along its [51-2] zone axis. Neither cubic $\gamma\text{-Fe}_2\text{O}_3$ with a statistical distribution of cation vacancies over the octahedral sites nor Fe_3O_4 shows a similar agreement (17,24). In other high-resolution TEM images, we observe particles with lattice plane distances of 4.97 and 4.27 Å that also belong uniquely to the tetragonal superstructure phase of $\gamma\text{-Fe}_2\text{O}_3$ (see following table 1 for comparison). Interestingly, it has been reported that this ordered superstructure phase occurs only in particles with diameters larger than 100 nm (25).

Table 1

| experimental | $\gamma\text{-Fe}_2\text{O}_3$ (cubic) | $\gamma\text{-Fe}_2\text{O}_3$ (tetragonal) | Fe_3O_4 |
|-----------------------------|--|---|-------------------------|
| $4.97 \pm 0.05 \text{ \AA}$ | | 5.01 (104) | |
| $4.77 \pm 0.05 \text{ \AA}$ | 4.82 (111) | 4.82 (113) | 4.85 (111) |
| $4.27 \pm 0.05 \text{ \AA}$ | | 4.30 (105), (114) | |
| $4.11 \pm 0.05 \text{ \AA}$ | | 4.12 (201) | |
| $2.86 \pm 0.05 \text{ \AA}$ | 2.95 (220) | 2.93 (221), (108) | 2.97 (220) |
| | | 2.87 (222) | |
| $2.39 \pm 0.05 \text{ \AA}$ | 2.41 (222) | 2.43 (305), (314) | 2.42 (222) |
| | | 2.41 (226) | |
| | | 2.40 (1010), (218) | |

Preparation of Metal Cupferron Precursors

Example 1. Synthesis of FeCup_3

The procedure described in the literature (26), was used to prepare the FeCup_3 complex. 1.12 g $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ were dissolved in 280 ml of 1% HCl in H_2O . To this solution, 140 ml conc. HCl were added, and this mixture was diluted with 525 ml H_2O and cooled in a fridge for about 15 min. Then 3 g ammonium cupferron dissolved in 100 ml H_2O were added dropwise from a burette yielding a red-brown precipitate. After 15 min of standing, the precipitate was filtered and dissolved in CHCl_3 . Water was removed in a separation funnel and the resulting deep-red solution was concentrated to about 5 – 10 ml in a rotavapor and additionally filtered with a glass filter. Hexane was then added until the solution became slightly turbid and the flask was placed into a fridge at -20°C . Within one day, large deep-red crystals grew which were isolated by decanting and dried in vacuum at 40°C . The yield of this product was typically 60 – 80 % with respect to iron. The experimental powder x-ray diffraction pattern (see fig. 8, left) agrees very well with calculated patterns based on single crystal structure data.(12) The results of the elemental analysis (calc. values in brackets) are for FeCup_3 : 12.5 % (12.0 %) Fe, 46.1 %

(46.3 %) C, 17.5 % (18.0 %) N, and 3.4 % (3.2 %) H. The FT-IR spectrum in fig. 9 (left) agrees well with results in literature (15) and shows the Fe-O stretch band at 427 cm^{-1} .

Example 2. Synthesis of MnCuP_2

Adding 6 g ammonium cupferron dissolved in 200 ml H_2O to a solution of 1.80 g $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ in 700 ml H_2O yielded an orange precipitate, which was isolated after 15 min. by filtration. This precipitate was dried at 20 mtorr at room temperature for several hours and the yield was typically about 50 % with respect to manganese. The experimental powder x-ray diffraction pattern (see fig. 8, middle) agrees very well with calculated patterns based on single crystal structure data.(14) The results of the elemental analysis (calc. values in brackets) are for MnCuP_2 : 17.2 % (16.2 %) Mn, 41.6 % (43.8 %) C, 16.4 % (17.0 %) N, 3.27 % (3.1 %) H. The FT-IR spectra of this compound is displayed in fig. 9 (middle) and shows the Mn-O stretch band at 405 cm^{-1} which is in agreement with literature results.(15)

Example 3. Synthesis of CuCuP_2

CuCuP_2 was prepared by adding dropwise 6 g ammonium cupferron dissolved in 200 ml H_2O to a solution of 1.54 g $\text{CuCl}_2 \cdot 4\text{H}_2\text{O}$ in 1.4 l H_2O . The resulting blue-gray precipitate was filtered after 15 min and dissolved in pyridine yielding a deep green solution. The solution was concentrated in a rotavapor and filtered with a glass filter. To this solution a mixture of n-butanol and hexane was added until the solution was slightly turbid. After one day in a fridge at $-20\text{ }^\circ\text{C}$ the solution contained large deep-green crystals which were isolated from the supernatant by decanting and dried at $40\text{ }^\circ\text{C}$ under

vacuum. The yield of the resulting blue-gray powder was typically 50 – 70 % with respect to copper. The experimental powder x-ray diffraction pattern (see fig. 8, right) agrees very well with calculated patterns based on single crystal structure data.(13) The results of the elemental analysis (calc. values in brackets) are for CuCup₂: 19 % (18.8 %) Cu, 43.1 % (42.7 %) C, 15.8 % (16.6 %) N, and 3.3 % (3.0 %) H. Fig. 9 (right) shows the FT-IR spectrum of the complex which agrees well with literature results (15) and shows the Cu-O stretch vibration at 437 cm⁻¹.

Example 4. Synthesis of CoCup₂

2.14 g CoCl₂· 6H₂O are dissolved in 1.4 l H₂O and 6 g Cupferron dissolved in 200 ml H₂O are added dropwise. The resulting solution showed a deep-red color but no precipitate. Consequently, additional 2.28 g CoCl₂· 6H₂O and 6 g Cupferron were added resulting in a pinkish precipitate while standing overnight. The precipitate was filtrated and recrystallized from pyridine.

Example 5. Synthesis of CdCup₂

1.66 g CdCl₂ are dissolved in 1.4 l H₂O and 6 g Cupferron dissolved in 200 ml H₂O are added dropwise. The resulting precipitate is filtrated. X-ray diffraction shows a crystalline product which is used without further purification.

Preparation of Surfactant-Capped γ -Fe₂O₃ Nanocrystals

Example 6. Preparation of about 6 – 7 nm γ -Fe₂O₃ Nanocrystals capped by trioctylamine

To remove oxygen and water, 7 g of trioctylamine was heated to 100 °C for 1 – 1.5 h and repeatedly evacuated to 20 mtorr and purged with Ar. A solution of 0.3 M FeCup₃ in octylamine was treated the same way at 60 °C. The reaction was initiated by the rapid injection of 4 ml of FeCup₃ stock solution into the trioctylamine at 300 °C under vigorous magnetic stirring and an Ar atmosphere. A color change of the liquid from colorless to dark-brown and the evolution of gas indicated the decomposition of the metal cupferron complex. After heating for 30 min. at 225 °C, the reaction was stopped and the liquid was allowed to cool down. At room temperature the flask contained nanocrystals of iron oxide, both in a dark-brown, clear liquid supernatant and a precipitate. The latter results from the high concentration of nanocrystals and their limited solubility in trioctylamine at low temperature. Adding 1 – 2 ml of organic solvents like toluene, hexane, CHCl₃, etc. to this precipitate yielded clear, deep-brown dispersions of iron oxide nanocrystals which were stable for weeks at room temperature. Low-resolution TEM imaging revealed the presence of iron oxide nanocrystals with an average size of 6.7 ± 1.4 nm (see fig. 2, left). By addition of a threefold volume excess of methanol, the iron oxide nanocrystals could be reprecipitated as a brown powder. Adding methanol to the supernatant of the reaction lead to a brown precipitate of iron oxide nanocrystals, which could also be redispersed and reprecipitated by suitable solvents. For both fractions, dispersion and reprecipitation could be repeated several times.

Example 7 Preparation of about 6 – 7 nm γ -Fe₂O₃ Nanocrystals capped by hexadecylamine

To remove oxygen and water, 7 g of hexadecylamine was heated to 100 °C for 1 – 1.5 h and repeatedly evacuated to 20 mtorr and purged with Ar. A solution of 0.3 M FeCup₃ in octylamine was treated the same way at 60 °C. The reaction was initiated by the rapid injection of 2 ml of FeCup₃ stock solution into the hexadecylamine at 300 °C under vigorous magnetic stirring and an Ar atmosphere. A color change of the liquid from colorless to dark-brown and the evolution of gas indicated the decomposition of the metal cupferron complex. After heating for 60 min. at 265 °C, the reaction was stopped and the liquid was allowed to cool down. At about 100 °C the reaction mixture was transferred into an excess of methanol (3 : 1) yielding a brown precipitate and a clear yellow-brown supernatant. After isolating the precipitate by centrifugation and discarding the supernatant, the precipitate can be dispersed in organic solvents like toluene, chloroform, hexane etc. Adding methanol to this dispersion yields again a brown precipitate. Redispersion and reprecipitation by suitable solvents could be repeated several times.

Example 8 Preparation of about 5 nm γ -Fe₂O₃ nanocrystals capped by hexadecylamine

To remove oxygen and water, 7 g of hexadecylamine was heated to 100 °C for 1 – 1.5 h and repeatedly evacuated to 20 mtorr and purged with Ar. A solution of 0.3 M FeCup₃ in octylamine was treated the same way at 60 °C. 2 ml of 0.3 M FeCup₃/Octylamine were added to the hexadecylamine at 100 °C and the solution was heated to 280 °C under vigorous magnetic stirring and an Ar atmosphere. Upon reaching

140 – 160 °C, gas evolution indicated the onset of the precursor decomposition. After about 12 min. of heating, the liquid reached a temperature of 280 °C and was refluxed at this temperature for another 48 min. After the heating was stopped, the reaction mixture was transferred at 100 °C into an excess of methanol (2:1). The resulting precipitate was isolated by centrifugation and could be redispersed in toluene, hexane, chloroform etc. By adding methanol to this dispersion, the nanocrystals could be reprecipitated. Redispersion and reprecipitation could be repeated several times.

Example 9 Preparation of about 9 nm γ -Fe₂O₃ nanocrystals capped by hexadecylamine

To remove oxygen and water, 7 g of hexadecylamine was heated to 100 °C for 1 – 1.5 h and repeatedly evacuated to 20 mtorr and purged with Ar. A solution of 0.3 M FeCup₃ in octylamine was treated the same way at 60 °C. The reaction was initiated by the rapid injection of 2 ml of FeCup₃ stock solution into the hexadecylamine at 300 °C under vigorous magnetic stirring and an Ar atmosphere. A color change of the liquid from colorless to dark-brown and the evolution of gas indicated the decomposition of the metal cupferron complex. After 6 min. an additional 2 ml of stock solution were added dropwise within the time range of 3 min. Additional slow injections of 2 ml stock solution took place 2 more times at 14 min. and 50 min. after the initial injection, respectively. After the last injection was finished, the liquid was heated for another 20 min. before heating was stopped and the liquid was allowed to cool down. At about 100 °C the reaction mixture was transferred into an excess of methanol (3 : 1) yielding a brown precipitate and a clear yellow-brown supernatant. After isolating the precipitate by centrifugation and discarding the supernatant, the precipitate can be redispersed in

organic solvents like toluene, chloroform, hexane etc. Adding methanol to this dispersion yields again a brown precipitate. Redispersion and reprecipitation by suitable solvents could be repeated several times.

Example 10 Preparation of about 12 nm Mn_3O_4 Nanocrystals capped by hexadecylamine

To remove oxygen and water, 7 g of trioctylamine was heated to 100 °C for 1 – 1.5 h and repeatedly evacuated to 20 mtorr and purged with Ar. A solution of 0.3 M MnCuP_2 in octylamine was treated the same way at 60 °C. The reaction was initiated by the rapid injection of 4 ml of MnCuP_2 stock solution into the trioctylamine at 360 °C under vigorous magnetic stirring and an Ar atmosphere. A color change of the liquid from colorless to dark-brown and the evolution of gas indicated the decomposition of the metal cupferron complex. The liquid was refluxed for 10 min. at 275 °C before heating was stopped. At room temperature the flask contained nanocrystals of manganese oxide, both in an orange-brown, clear liquid supernatant and a brown precipitate. Adding 1 – 2 ml of organic solvents like toluene, hexane, CHCl_3 , etc. to this precipitate yielded clear, deep-brown dispersions of manganese oxide nanocrystals. By addition of a threefold volume excess of methanol, the manganese oxide nanocrystals could be reprecipitated as a brown powder. Adding methanol to the supernatant of the reaction lead to a brown precipitate, which could also be redispersed and reprecipitated by suitable solvents. For both fractions, dispersion and reprecipitation could be repeated several times. Low-resolution TEM images of this sample are shown in fig. 2 (middle). The average particle size and size-distribution as determined from this image is 12.0 ± 4.7 nm.

Example 11 Preparation of about 7 nm Cu₂O Nanocrystals capped by hexadecylamine

To remove oxygen and water, 5.5 g of hexadecylamine was heated to 100 °C for 1 – 1.5 h and repeatedly evacuated to 20 mtorr and purged with Ar. A solution of 0.3 M CuCup₂ in octylamine was treated the same way at 60 °C. 2 ml of a 0.3 M solution of CuCup₂ in octylamine were injected into 5.5 g hexadecylamine at 250 °C causing the temperature to drop to about 215 °C. The reaction was stopped by removing the heat as soon as the temperature reached again 230 °C. At about 100 °C, the liquid was transferred into an excess of methanol (3:1) yielding a brown precipitate which was isolated by centrifugation. This precipitate could be redispersed in organic solvents like toluene, hexane, chloroform and again reprecipitated by addition of methanol. The average particle size and size-distribution as determined from low-resolution TEM imaging is 6.9 ± 2.5 nm.

Example 12 Preparation of about 20 nm CdO Nanocrystals capped with hexadecylamine

To remove oxygen and water, 7 g of hexadecylamine was heated to 100 °C for 1 – 1.5 h and repeatedly evacuated to 20 mtorr and purged with Ar. A solution of 0.3 M CdCup₂ in octylamine was treated the same way at 60 °C. 3 ml of a 0.3 M solution of CdCup₂ in octylamine were injected into 7 g hexadecylamine at 300 °C. The liquid was refluxed for 30 min. at 245 °C before heating was stopped. At 100 °C the liquid was transferred into an excess of methanol (3:1). The resulting brown precipitate was isolated by centrifugation and dispersed in toluene, chloroform or hexane. By addition of methanol, a brown precipitate could be recovered.

Example 13 Preparation of 9 nm CoO Nanocrystals capped with trioctylamine

To remove oxygen and water, 7 g of trioctylamine was heated to 100 °C for 1 – 1.5 h and repeatedly evacuated to 20 mtorr and purged with Ar. A solution of 0.3 M CoCup₂ in octylamine was treated the same way at 60 °C. 4 ml of this solution were injected at 300 °C into the trioctylamine and refluxed for 20 min. at 230 °C. The liquid was allowed to cool to 100 °C and transferred into an excess of methanol (3:1). The resulting grey precipitate could be redispersed in toluene, chloroform or hexane. By addition of methanol, the nanocrystals could be recovered as a powder.

The preferred metals for use in preparing the M^XCup_X precursor for use in the process of this invention are transition metals, more preferably either Fe, Mn, or Cu.

Additionally, while the Cup compound most commonly used in the formation of the precursor is N-nitroso-N-phenyl-hydroxylamine, other N-substituted N-Nitroso hydroxylamine compounds can be used. Any compound having the head group (O-N-N=O) can be used. Broadly speaking, any N-substituted N-nitroso-hydroxylamine of the formula RN₂O₂ where R is a phenyl, benzyl, naphthyl, biphenyl, methyl, propyl, etc. would be suitable for use. Specific compounds include, for example, N-nitroso-N-phenyl-hydroxylamine, N-nitroso-N[1]-naphthyl-hydroxylamine, N-nitroso-N-biphenyl-4-yl-hydroxylamine, N-nitroso-N[2]-fluorenyl-hydroxylamine, N-nitroso-N-benzyl-hydroxylamine, N-nitroso-N-(4-nitrophenyl)-hydroxylamine, N-nitroso-N-trityl-hydroxylamine, and N-nitroso-N-isopropyl-hydroxylamine, their salts, such as ammonium salts, and the like.

The coordinating surfactant is preferably amine based, and most preferably is trioctylamine, or hexadecylamine. Other suitable amines include dioctylamine, and dibenzylamine. Still other suitable surfactants include primary, secondary or tertiary alkyl- or aryl- amines; primary, secondary or tertiary alkyl- or aryl- phosphines, such as tributylphosphine, triphenylphosphine; primary, secondary or tertiary alkyl- or aryl- phosphine oxides such as octylphosphine oxide, and dihexylphosphine oxide and trioctylphosphine oxide; dialkyl-, diaryl- or aryl-alkyl-ethers such as dioctylether, and dibenzylether; carboxylic acids such as oleic acid, and lauric acid; and nitriles such as pentadecanitrile, as well as derivatives and mixtures thereof. Whatever surfactant that is used, it should have a polar head group attached to an apolar alkyl or aryl rest.

The process is carried out in an inert atmosphere in the absence of water, air, or oxygen. The preferred inert atmosphere is argon gas, but nitrogen or any other inert gas can be used.

The mixture of metal cupferron complex and coordinating surfactant is heated to a temperature sufficient to cause the thermal decomposition of the precursor and formation of the nanocrystals. In general, the temperature to which the mixture is heated can range from 150 to 400 degrees C, preferably from 220 to 350 degrees C, and most preferably from 250 to 300 degrees C. The exact temperature to which the mixture is heated will depend on the reactants and the duration that heat is applied.

The nanocrystals produced by the process of this invention range from about 2 to about 20 nm in diameter. Crystals of varying sizes within this range can be achieved by varying the reaction conditions, such as time, temperature, choice of surfactant and precursor to surfactant ratio, as will be apparent to those skilled in the art.

The nanocrystals produced by the method of the invention are dispersable in organic solvents such as toluene, chloroform, and hexane and other aromatic, halogenated or aliphatic hydrocarbons.

Broadly speaking, the process of the invention comprising mixing the metal cupferron precursor with the coordinating surfactant, and heating the mixture until decomposition of the precursor occurs, and formation of the desired nanocrystals is achieved.. The preferred mode by which this is accomplished is to inject the precursor into a hot liquid surfactant and maintain it at the desired temperature and for a sufficient period of time for the reaction to occur. Thus the term "mixing" as used herein, also includes injection of the precursor into a hot liquid surfactant. Any other means of mixing the two can be used, however.

It will be understood by those skilled in the art that various modifications can be made in the process and compounds of the invention without departing from the spirit and scope thereof.

We claim:

1. A process for making dispersable surfactant capped nanocrystals of metal oxides which comprises : (a) mixing a solution of a metal cupferron precursor complex of the formula $M^X\text{Cup}_X$, wherein M^X is a metal ion in the oxidation state X selected from the group consisting of elements in Group 2, Group 3 – 12 of the 4th period, Group 3 – 6 of the 5th and 6th period, Group 10 – 12 of the 5th period, Group 12 of the 6th period, and Group 13th to 15th, and the Lanthanide and Actinide series of the periodic table, and Cup is a N-substituted N-nitroso hydroxylamine, with a coordinating surfactant , and (b) heating the mixture at a temperature and for a sufficient period of time to cause thermal decomposition of the $M^X\text{Cup}_X$ precursor and formation of the desired nanocrystals.
2. The process of Claim 1 wherein said the reaction is conducted in an inert atmosphere.
3. The process of Claim 2 wherein said inert atmosphere is argon or nitrogen gas.
4. The process of Claim 1 wherein said reaction is conducted in the absence of water, air or oxygen.
5. The process of Claim 1 wherein the mixture is heated to or maintained at a temperature ranging from about 150 °C to about 400 °C.
6. The process of Claim 1 wherein M is Fe .
7. The process of Claim 1 wherein M is Mn .
8. The process of Claim 1 wherein M is Cu .

9. The process of Claim 1 wherein said coordinating surfactant is an organic molecule consisting of a polar headgroup and an apolar group providing stabilization against coagulation and precipitation of particles.

10. The process of Claim 9 wherein said coordinating surfactant is hexadecylamine or trioctylamine.

11. The process of Claim 1 wherein said N-substituted N-nitroso hydroxylamine is N-nitroso-N-phenyl hydroxylamine (Cupferron).

12. The process of Claim 1 wherein M is Fe , Cup is N- nitroso-N-phenyl hydroxylamine, and the coordinating surfactant is hexadecylamine.

13. A process for making dispersable surfactant capped nanocrystals of metal oxides with non-hydroxylated particle surfaces which comprises mixing a solution of a metal cupferron complex of the formula $M^X\text{Cup}_x$, wherein M^X is a metal ion in the oxidation state X selected from the group consisting of elements in Group 2, Group 3 – 12 of the 4th period, Group 3 – 6 of the 5th and 6th period, Group 10 – 12 of the 5th period, Group 12 of the 6th period, and Group 13th to 15th, and the Lanthanide and Actinide series of the periodic table, and Cup is cupferron, into an amine based coordinating surfactant, at a temperature ranging from about 250 °C to about 300 °C, and allowing the reaction to proceed for a period of time sufficient to cause thermal decomposition of said $M^X\text{Cup}_x$, and formation of the desired nanocrystals.

14. A surfactant capped nanocrystal made in accordance with the process of Claim 1.

15. A process for making dispersable surfactant capped nanocrystals of transition metal oxides with non-hydroxylated particle surfaces which comprises injecting a

solution of a metal cupferron complex of the formula $M^X\text{Cup}_x$, wherein M is selected from the group consisting of Fe, Mn, and Cu, and Cup is N-nitroso-N-phenyl hydroxylamine, into a coordinating surfactant, the injection reaction being conducted at a temperature ranging from about 220 °C to about 350 °C, for a period of time sufficient to complete the reaction.

16. A process for making surfactant capped nanocrystals of transition metal oxides which comprises injecting a solution of a metal cupferron complex of the formula $M^X\text{Cup}_x$, wherein M is selected from the group consisting of Fe, Mn, and Cu, and Cup is N-nitroso-N-phenyl hydroxylamine, into an amine based coordinating surfactant, the injection reaction being conducted at a temperature ranging from about 150 °C to about 400 °C, for a period of time sufficient to complete the reaction.

17. The process of Claim 1 wherein the numerical value of X ranges from 1 to 4.

Abstract of the Disclosure

Disclosed is a process for making surfactant capped nanocrystals of metal oxides which are dispersable in organic solvents. The process comprises decomposing a metal cupferron complex of the formula $M^X\text{Cup}_x$, wherein M is a metal, and Cup is a N-substituted N-Nitroso hydroxylamine, in the presence of a coordinating surfactant, the reaction being conducted at a temperature ranging from about 150 to about 400 C, for a period of time sufficient to complete the reaction. Also disclosed are compounds made by the process.

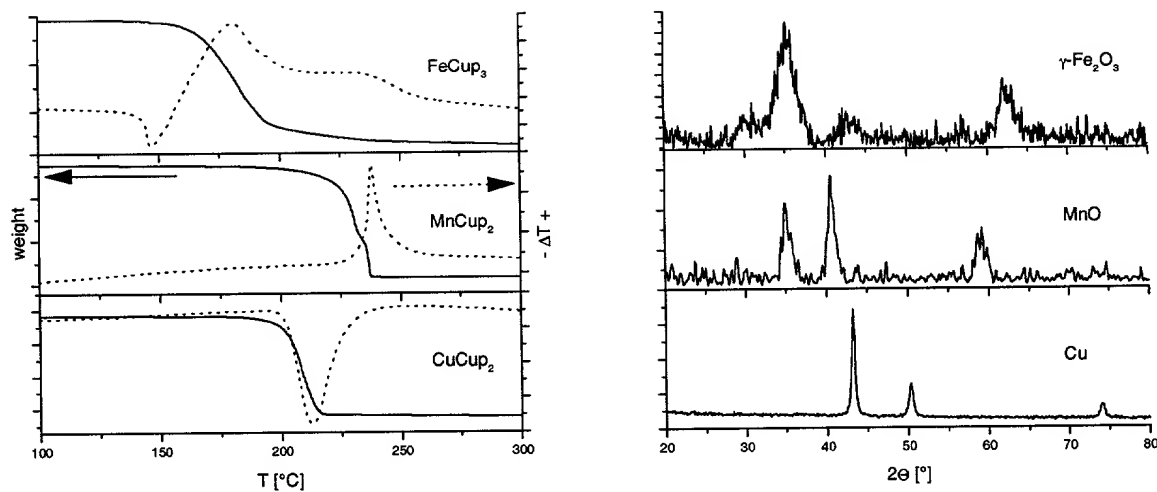


Figure 1 Left) Thermogravimetric analysis and Differential Thermal Analysis of powders of FeCuP_3 , MnCuP_2 and CuCuP_2 . Right) Powder x-ray diffraction patterns (Cu K_{α} radiation) of the respective decomposition products.

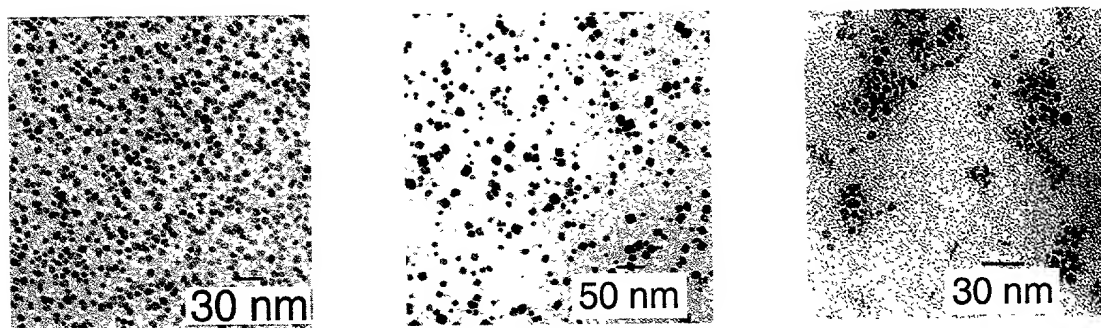


Figure 2 Low-resolution TEM images of $\gamma\text{-Fe}_2\text{O}_3$ (left), Mn_3O_4 (middle) and Cu_2O (right) nanocrystals. The average particle sizes and standard deviations are 6.7 ± 1.4 nm for $\gamma\text{-Fe}_2\text{O}_3$, 12.0 ± 4.7 nm for Mn_3O_4 and 6.9 ± 2.5 nm for Cu_2O .

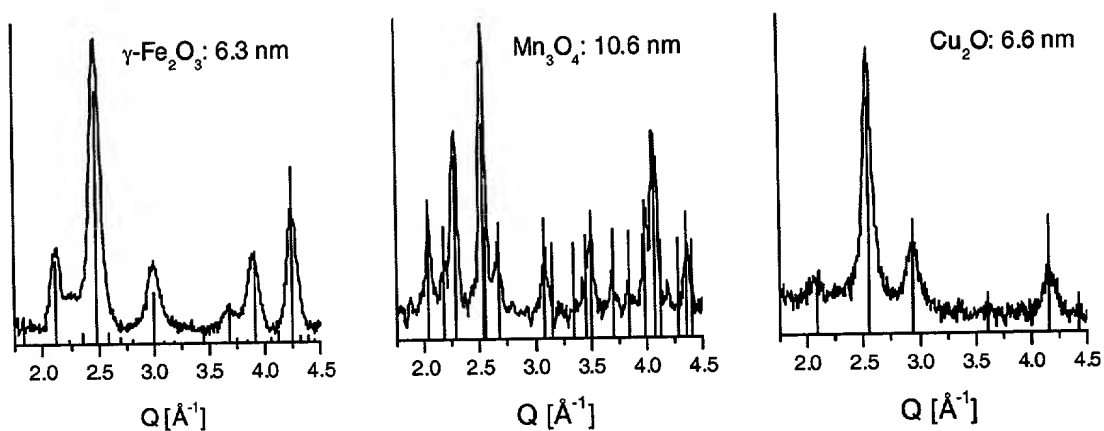


Figure 3 XRD patterns of $\gamma\text{-Fe}_2\text{O}_3$ (left), Mn_3O_4 (middle) and Cu_2O (right) nanocrystals and expected lattice reflections of the respective bulk phases.

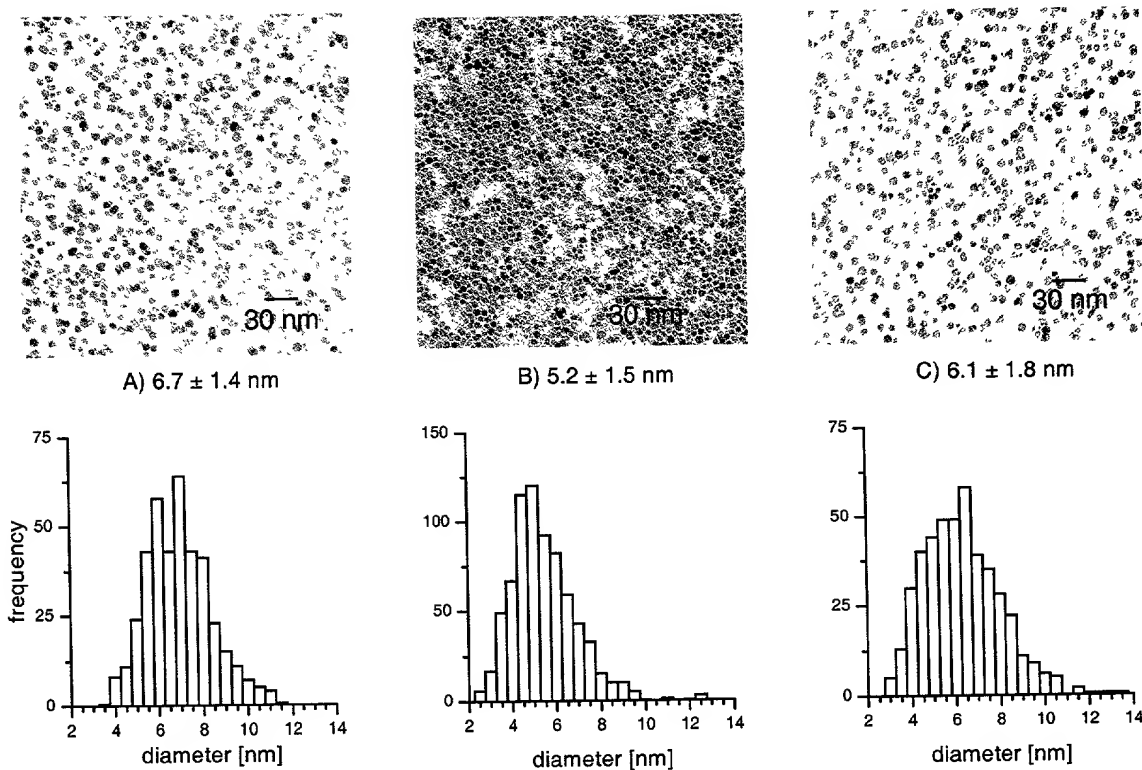


Figure 4 Low-resolution TEM images and respective diameter histograms of samples prepared under different conditions: A) Injection of 4 ml 0.3 M FeCuP_3 / octylamine into 7 g trioctylamine at 300 °C and refluxing at 225 °C for 30 min. B) Injection of 4 ml 0.3 M FeCuP_3 / octylamine into 7 g trioctylamine at 250 °C and refluxing at 200 °C for 30 min. C) Injection of 4 ml 0.3 M FeCuP_3 / octylamine into 7 g trioctylamine at 250 °C and refluxing at 200 °C for 5 min, then, additional injection of 2 ml stock solution and refluxing for 25 min at 200 °C.

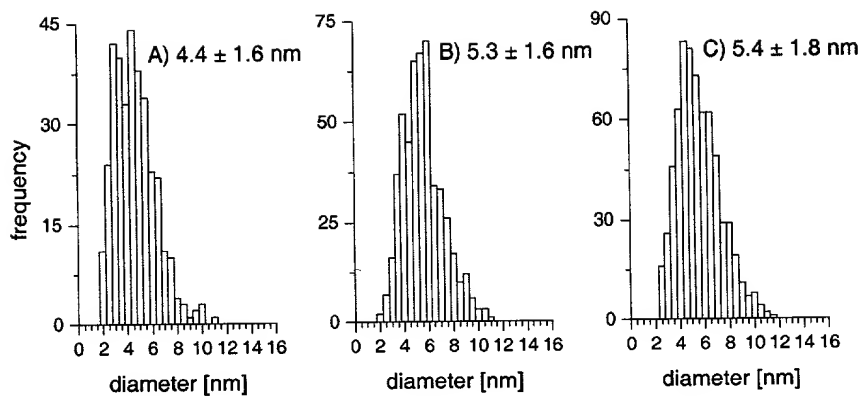


Figure 5 The time evolution of the particle size during refluxing at 200 °C as determined from low-resolution TEM imaging of aliquots taken at specific times from the reaction solution: A) 5 min after injection. B) 10 min after injection C) 30 min after injection of 4 ml 0.3 M FeCup₃ / octylamine into 7 g trioctylamine at 250 °C.

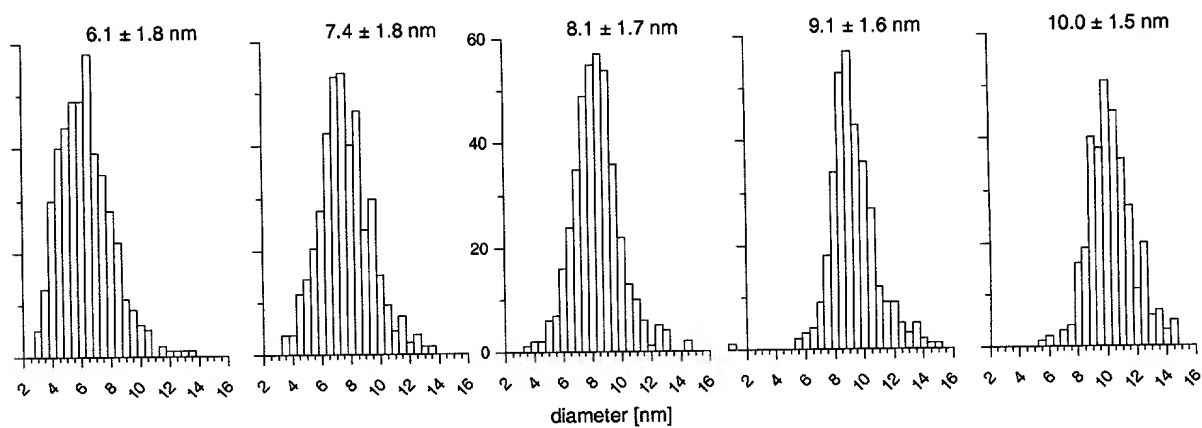


Figure 6 Size evolution of $\gamma\text{-Fe}_2\text{O}_3$ nanocrystals isolated by subsequent extractions of the reaction precipitate with toluene. The reaction conditions were as described in fig. 4C).

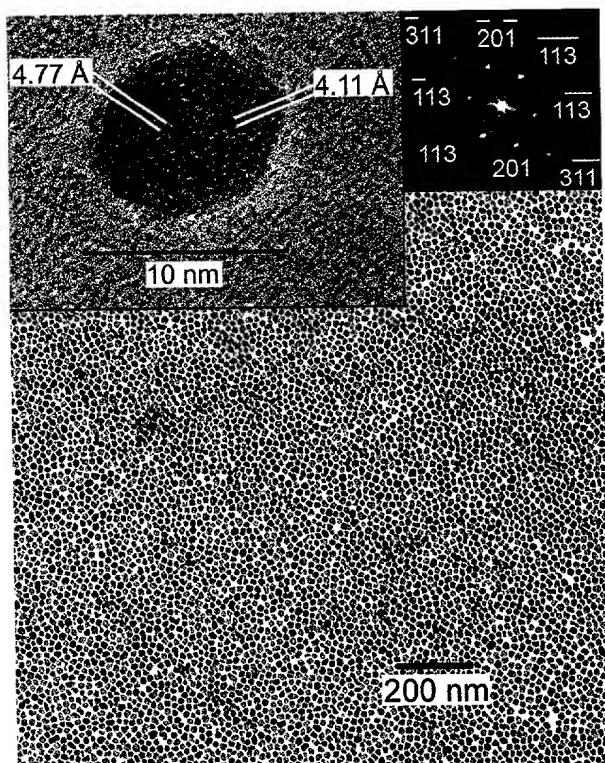


Figure 7 Low-resolution TEM image of a monolayer of individual $\gamma\text{-Fe}_2\text{O}_3$ nanocrystals (10.0 ± 1.5 nm) covering an area bigger than $2 \mu\text{m}^2$. Top left: High-resolution TEM image of one of the nanocrystals in this sample. The indicated lattice plane distances correspond to the (113) and (201) lattice planes of tetragonal $\gamma\text{-Fe}_2\text{O}_3$ with ordered superlattice of the cation vacancies. Top right: FFT of the high-resolution TEM image looking down the [51-2] zone-axis.

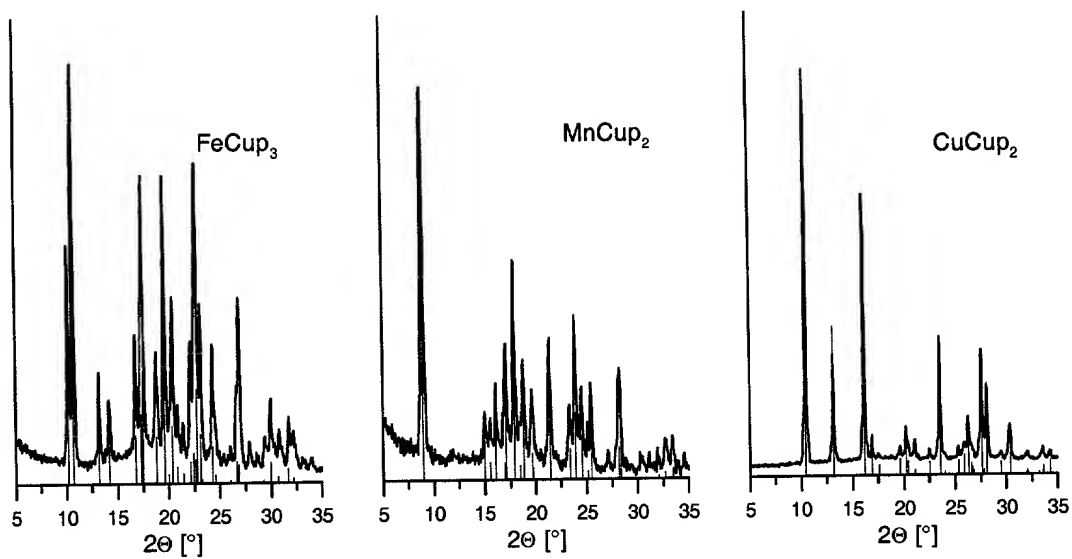


Figure 8 Powder XRDs (Cu K_α radiation) of metal cupferronates.

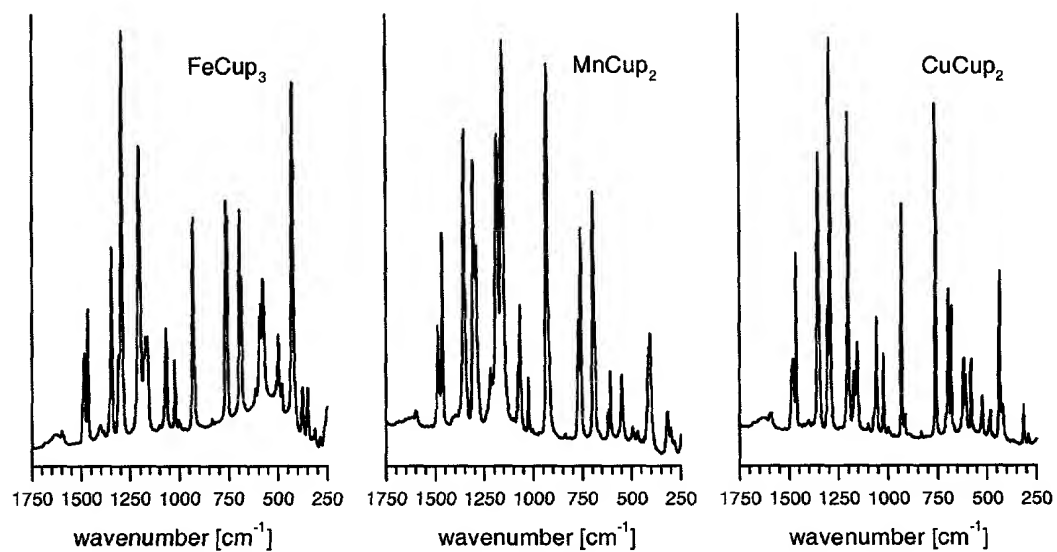


Figure 9 FT-IR spectra of metal cupferron complexes in KBr.

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant(s): Jorg Rockenberger
Erik C. Scher
A. Paul Alivisatos

For: **A PROCESS FOR MAKING SURFACTANT CAPPED NANOCRYSTALS**

POWER OF ATTORNEY BY ASSIGNEE
AND EXCLUSION OF INVENTOR(S) UNDER RULE 32

Hon. Commissioner of Patents and Trademarks
Washington, D.C. 20231

Dear Sir:

The undersigned assignee of the entire interest in the above-identified subject application hereby appoints:

| | |
|-------------------|-------------------|
| David J. Aston | (Reg. No. 28,051) |
| Paul R. Martin | (Reg. No. 24,593) |
| Henry P. Sartorio | (Reg. No. 28,535) |

all of The Lawrence Berkeley National Laboratory

as its representatives to prosecute this application and to transact all business in the Patent Office connected therewith, said appointment to be to the exclusion of the inventors and their attorneys in accordance with the provisions of Rule 32 of the Patent Office Rules of Practice.

Please direct all telephone calls to the above at 510-486-7058
and all correspondence relative to said application to the following address:

Patent Counsel
Lawrence Berkeley National Laboratory
One Cyclotron Road, M/S 90-1121
Berkeley, California 94720

In accordance with 37 CFR 3.73 the assignee hereby certifies that the evidentiary documents with respect to its ownership have been reviewed and that, to the best of assignee's knowledge and belief, title is in the assignee seeking to take this action.

ASSIGNEE: THE REGENTS OF THE UNIVERSITY OF CALIFORNIA

Signature: _____

Paul R. Martin

Title: Attorney, Patent Counsel

Address: Lawrence Berkeley National Laboratory, One Cyclotron Road
M/S 90-1121
Berkeley, California 94720